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CALCULATION OF OPTIMUM EFFICIENCY FOR A SERIES OF LARGE-HUB PROPELLERS FOR APPLICATION TO TANDEM PROPULSION OF A SUBMERGED BODY OF REVOLUTION

by

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August 1964

Report 1826

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NOTATION

A	Propeller swept area, $(1 - x_h^2)\, A_o$
A_e	Expanded area of propeller blades
A_o	Propeller disk area, $\frac{\pi D^2}{4}$
C_P	Propeller power coefficient, $\frac{2\pi Q n}{1/2\, \rho\, A\, V_a^3}$
C_T	Propeller thrust coefficient, $\frac{T}{1/2\, \rho\, A\, V_a^2}$
c	Ratio of nonviscous to viscous thrust, $\frac{C_{Ti}}{C_T}$
D	Propeller diameter or maximum diameter of a body of revolution
J	Speed coefficient, $\frac{V_a}{nD}$
L	Length of a body of revolution
ℓ	Blade section length
n	Propeller rate of revolution
P_D	Power delivered to propeller, $2\pi Q n$
P_E	Effective (tow rope) power, $R_T\, V$
Q	Propeller torque
R_o	Propeller radius
R_T	Total resistance
T	Propeller thrust
t	Thrust-deduction coefficient, $(1 - \frac{R_T}{T})$
V	Ship speed
V_a	Speed of advance
V_x	Axial component of local velocity

$V_{\forall}/V$	Volume mean velocity ratio
X,Y	Dimensional coordinates
x	Propeller radius fraction (also nondimensional length)
Z	Number of blades
β	Advance angle, $\tan^{-1}\frac{\lambda}{x}$
β_i	Hydrodynamic pitch angle (see Figure 5)
Γ	Circulation
ϵ	Section drag-lift ratio
η_B	Propeller efficiency in a wake (see Equation [5])
η_D	Propulsive coefficient, P_E/P_D
η_H	Hull efficiency, $\frac{(1-t)}{V_a/V}$
η_o	Propeller open-water efficiency, $\frac{T_o\ V_o}{2\pi Q_o n_o}$
λ	Advance coefficient, $\frac{V_a}{\pi\ nD}$

Additional subscripts

h	Propeller hub
i	Nonviscous
o	Open water (except A_o and R_o)
s	Based on ship speed

ABSTRACT

Calculations were performed to determine the efficiency of integral bow and stern propellers for a body of revolution. Such a propulsion system leads to propellers with large hubs relative to the tip diameter and a large number of blades. The calculations were carried out for a propeller with 13 blades with various tip diameters, blade areas, and rpm's. The series results are presented, analyzed, and applied to computing the propulsion performance of a hypothetical 250-foot tandem propeller submarine.

INTRODUCTION

To provide increased maneuverability at low speed for special purpose submarine designs, the Office of Naval Research has conducted studies of several new systems. One of these is known as the tandem propeller submarine (TPS).[1] This vehicle is controlled and propelled by a propeller located near the bow and an opposite turning propeller located near the stern.[*] Variations in blade pitch can be made either collectively or cyclically (as a function of blade angular position) for each propeller blade. The propeller location for this system results in propellers with relatively large hubs and a large number of blades. This report discusses a calculation procedure, and results obtained therefrom, for estimating the propulsion performance of such propellers.

To fulfill the objective of finding optimum propeller efficiency for large-hub propellers for propelling a submerged body of revolution, design calculations were performed covering a range of advance ratios and expanded-area ratios for body-propeller diameter ratios of 0.7 and 0.8. A submarine form belonging to TMB Series 58 was chosen for this study. Compared to the present approach of calculating optimum propeller efficiency for a systematic series, other investigations of TPS propeller performance have been (1) concerned primarily with estimating vehicle dynamics[2,3] where the contribution of the propeller to maneuvering and control characteristics was of prime interest and could be approximated, for the purpose, by

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[1]References are listed on page 26.

[*]U.S. Patent Number 3,101,066.

simple mathematical models of the propeller and (2) concerned with studying powering performance of a shrouded large-hub propeller system[4] in some detail but making no attempt to optimize the design.

Results of the present series are presented in nondimensional form as curves of optimum wake-adapted propeller efficiency as a function of the parameters investigated. To aid the designer, propeller efficiencies as a function of rpm are presented for a hypothetical 250-foot TPS operating submerged at a speed of 30 knots.

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STATEMENT OF PROBLEM

The problem is to find the most efficient wake-adapted propeller for a set of specified conditions. Essentially, the solution of this problem involves the following: Given an arbitrary inflow at the propeller disk, find the radial distribution of circulation along a propeller blade for minimum energy loss. In this report, the inflow at the propeller is obtained by determining the potential flow and boundary layer about a prescribed body using the methods of References 5 and 6, respectively. Lerbs' rigorous induction-factor method[7] is used to calculate the velocities at each blade section for the case of moderately loaded wake-adapted propellers. The required optimum radial distribution of bound circulation is based on the optimum distribution proposed by Lerbs.[7,8] Propeller performance in a real viscous flow is then calculated using NACA drag data.

Apart from the assumptions and limitations of the vortex theory as applied to moderately loaded propellers in a potential flow and of the theory of boundary layers[6] in a pressure gradient for bodies of revolution, the principal assumptions used herein are: (1) As applied to the tandem propeller submarine, mutual interference effects between bow and stern propellers are not important. This assumption seems justified in the present investigation since the spacing between propellers is about 6 diameters; (2) In calculating propeller speed-of-advance, the volume mean velocity is assumed equal to the effective inflow velocity; (3) Lerbs' theory can be applied with sufficient accuracy to large-hub propellers; and

(4) The real flow can be divided into a viscous part and a nonviscous (potential) part. This division is necessary because of the presence of the boundary layer.

BODY OF REVOLUTION

GEOMETRY OF HYPOTHETICAL TANDEM PROPELLER SUBMARINE

A mathematically defined body of revolution[9] of fineness ratio L/D = 7.34, belonging to TMB Series 58, was selected as the vehicle for the design computation of a series of bow and stern wake-adapted propellers. Table 1 contains the nondimensional offsets to the meridian profile and other geometrical coefficients for the body. As may be seen in an artist's drawing, Figure 1, the propeller hubs comprise an integral part of the hull of a TPS.

After considering the physical properties of a hypothetical TPS for an example, it was decided to use a 250-foot prototype with propellers at a bow location of X/L = 0.10 and a stern location of X/L = 0.80. A length of 250 feet gives a reasonable hull diameter of 34 feet for the 7.34 fineness ratio. This diameter compares to 32 feet for a 275-foot TPS with a fineness ratio of 8.59 postulated in Reference 3.

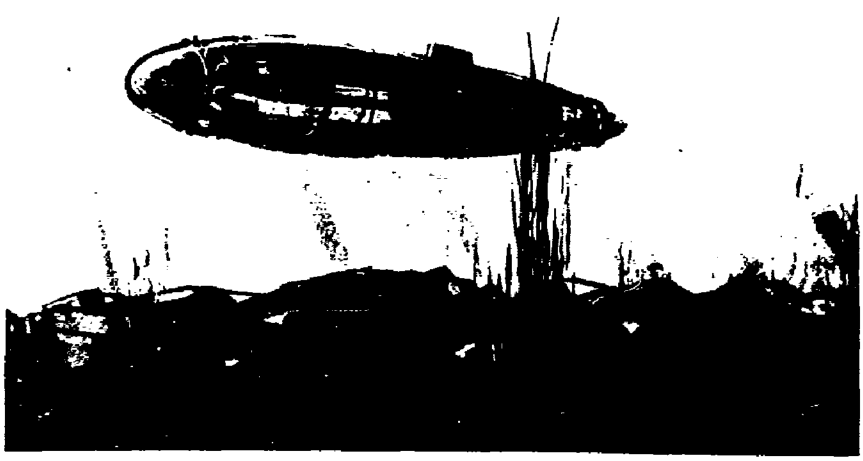

Figure 1 - Artist's Concept of Full-Size Tandem Propeller Submarine

(Courtesy of Naval Research Reviews)

TABLE 1

Offsets and Particulars for a TMB Series 58

x = X/L	y = Y/D	x = X/L	y = Y/D
0.00	0.0000	0.52	0.4818
0.02	0.1427	0.54	0.4755
0.04	0.2029	0.56	0.4684
0.06	0.2490	0.58	0.4603
0.08	0.2873	0.60	0.4513
0.10	0.3200	0.62	0.4414
0.12	0.3485	0.64	0.4305
0.14	0.3734	0.66	0.4187
0.16	0.3953	0.68	0.4058
0.18	0.4145	0.70	0.3919
0.20	0.4312	0.72	0.3768
0.22	0.4457	0.74	0.3605
0.24	0.4581	0.76	0.3429
0.26	0.4687	0.78	0.3239
0.28	0.4775	0.80	0.3036
0.30	0.4848	0.82	0.2817
0.32	0.4905	0.84	0.2582
0.34	0.4947	0.86	0.2330
0.36	0.4977	0.88	0.2060
0.38	0.4994	0.90	0.1771
0.40	0.5000	0.92	0.1461
0.42	0.4995	0.94	0.1131
0.44	0.4979	0.96	0.0778
0.46	0.4953	0.98	0.0401
0.48	0.4917	1.00	0.0000
0.50	0.4878		

Serial 40050060-73

Formula: $y^2 = a_1x + a_2x^2 + a_3x^3 + a_4x^4 + a_5x^5 + a_6x^6$

where:

$a_1 = 1.000$

$a_2 = +1.137153$

$a_3 = -10.774885$

$a_4 = +19.784286$

$a_5 = -16.792534$

$a_6 = +5.645977$

Wetted Surface Coefficient $\frac{S}{\pi LD} = 0.7324$

LCB, $\overline{x} = 0.4456$

L/D = 7.339

Note: This method of defining bodies of revolution is given in Reference 9.

VELOCITY PROFILE AT PROPELLER

Propellers of the type and location being investigated experience inflow velocities that are associated with a real flow. A solution for these inflow velocities is obtained by dividing the flow into a viscous part and a potential part as stated in Assumption 4. Numerical techniques that utilize a high-speed computer were used to obtain the streamflow and boundary-layer characteristics. Only a brief description of the methods used is presented since they are well described in the references.

Concerning the <u>viscous part</u>, Granville[6] has reviewed the subject of turbulent boundary layers in a pressure gradient and presented a method for calculating their most important characteristics. Velocity profiles within the boundary layer as determined by Granville's method, which is programmed for a high-speed computer at the Model Basin, were used to obtain the radial distribution of the axial component of the fluid velocity relative to the body.

Concerning the <u>potential part</u>, a solution for the potential flow about a body leads to a solution of the Laplace equation[10] subject to the boundary condition that the velocity normal to the body surface be zero. Methods for solving the direct problem of determining the flow about a prescribed axisymmetric body have been studied by many investigators, and recently Smith and Pierce[5] programmed a numerical solution for the aforementioned case. The potential due to a surface distribution of sources and the normal velocity at a point P outside the body, due to this source distribution, may be written in the form of a Fredholm integral equation of the second kind. Smith and Pierce used a set of linear algebraic equations to solve this integral equation.

The effect of the boundary layer on pressure distribution can be approximately taken into account in potential flow problems. Consideration of the influence of the boundary layer usually leads to an improvement in the accuracy of estimating the actual pressure distribution. In accounting for the difference between actual pressure and potential pressure, a so-called displacement thickness of the boundary layer is considered as part of the body. The potential flow calculations in this report were made for this altered (equivalent) body where the radius r^* to the surface of an equivalent body of revolution is defined[6] by

$$r^* = r_w + a^* \cos \alpha$$

where r_w is the radius of a body of revolution,

a^* is the displacement thickness of the boundary layer normal to the surface of an axisymmetric body, and

α is the angle of inclination of the body surface to the body axis.

IBM-7090 computer programs have been written for the methods discussed. Numerical results as obtained from these programs are presented in Figures 2 and 3 where the longitudinal velocity ratios V_x/V are those seen by a propeller at bow position X/L = 0.10 and at stern position X/L = 0.80 for hub ratios of 0.7 and 0.8, respectively. The velocity V_x is the axial component of the local velocity and the radius x is referred to the body axis. As can be seen from the figures, the velocity at the forward propeller is essentially free-stream velocity except very near the hub for both body-propeller diameter ratios. Examination of the velocity ratios at X/L = 0.8 shows that a somewhat higher velocity occurs for 0.7 diameter ratios than for 0.8 ratios at the same propeller radius fraction.

In this study (see Assumption 2, Statement of Problem), the effective inflow velocity is taken as the volume mean velocity. This quantity is defined by the following equation which applies to axisymmetric flow:

$$\frac{V_{\bar{v}}}{V} = \frac{2}{1 - x_h^2} \int_{x_h}^{1} \frac{V_x}{V} x \, dx \qquad [1]$$

Making use of Simpson's rule, $V_{\bar{v}}/V$ was computed from the curves of Figures 2 and 3 and has the following values:

Hub Ratio	Bow, X/L = 0.1	Stern, X/L = 0.8
x_h	$V_{\bar{v}}/V$	$V_{\bar{v}}/V$
0.7	0.995	0.893
0.8	0.993	0.835

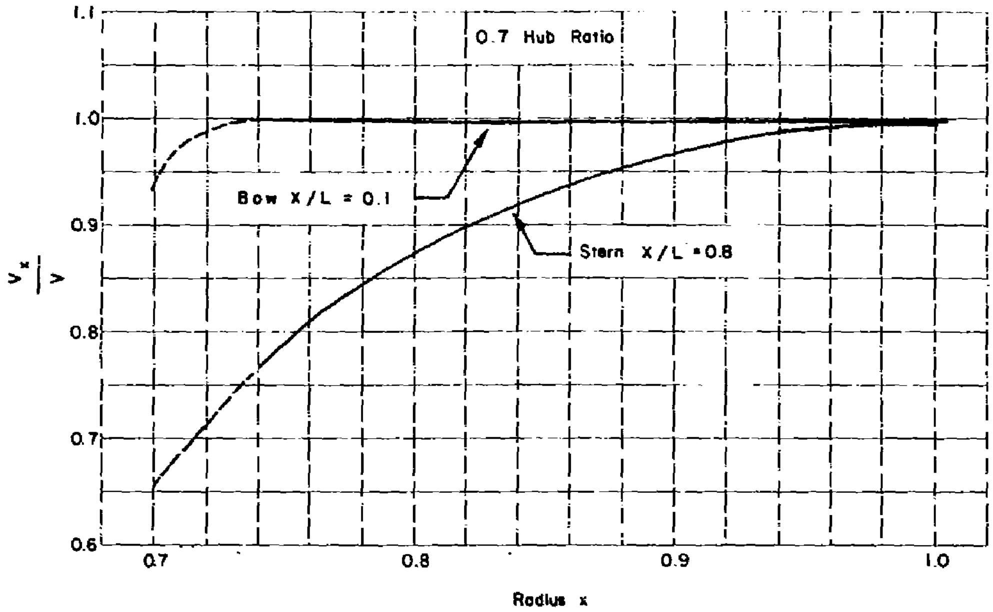

Figure 2 - Calculated Velocity Ratio as a Function of Propeller Radius Fraction, 0.7 Hub

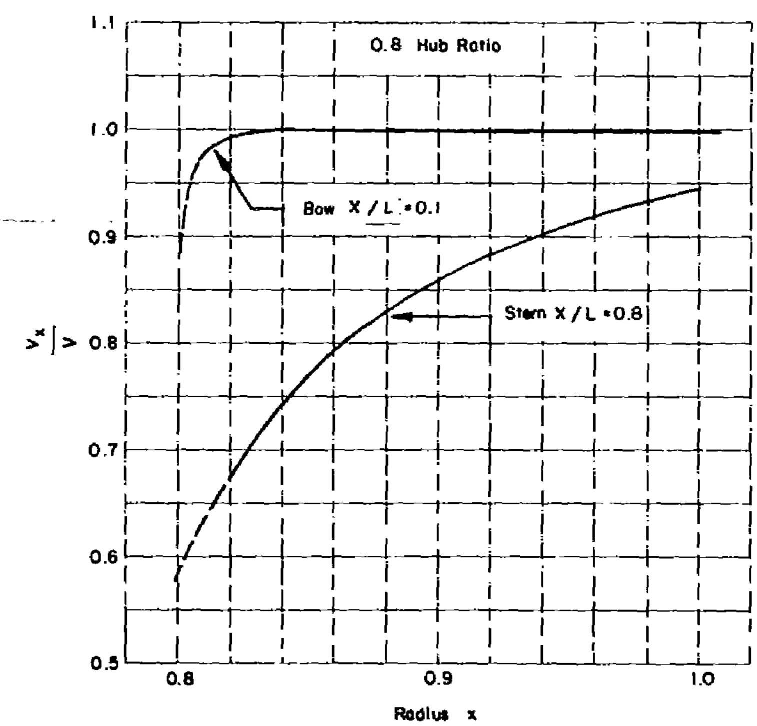

Figure 3 - Calculated Velocity Ratio as a Function of Propeller Radius Fraction, 0.8 Hub

GEOMETRY OF PROPELLER SERIES

Selection of the several geometric parameters was determined from the following considerations: Blade Outline - For mathematical convenience an elliptical expanded-blade outline was chosen. Number of Blades - In order to be comparable to other postulated TPS propellers,[3,4] the number of blades was taken to be 13 for each propeller. Body-propeller diameter ratios of 0.7 and 0.8 were selected as being practical;[3,4] larger values of this ratio do not appear acceptable from an efficiency standpoint.

A range of both expanded-area ratio A_e/A_o (values of 0.4, 0.5, and 0.6) and speed coefficient is covered by the series calculations. With regard to the range of A_e/A_o from 0.4 to 0.6, References 3 and 4 use $A_e/A_o \approx 0.10$ for which value one must assume very deep operation for no cavitation danger. Since a submarine must submerge and surface, it seems more realistic to select a more conservative value. It is of interest to note that as the propeller diameter is decreased the blade chord lengths should increase to satisfy the same cavitation criteria.

In this study an elliptical blade outline will be assumed (Figure 4) with a portion of the area equal to $0.45\,\frac{mM}{4}$, masked by the hub from $Y/M = -0.3$ to -0.5 and with local blade-section chord length ℓ equal to $2X$. Nondimensional blade-section lengths ℓ/D are given in terms of the propeller series parameters by

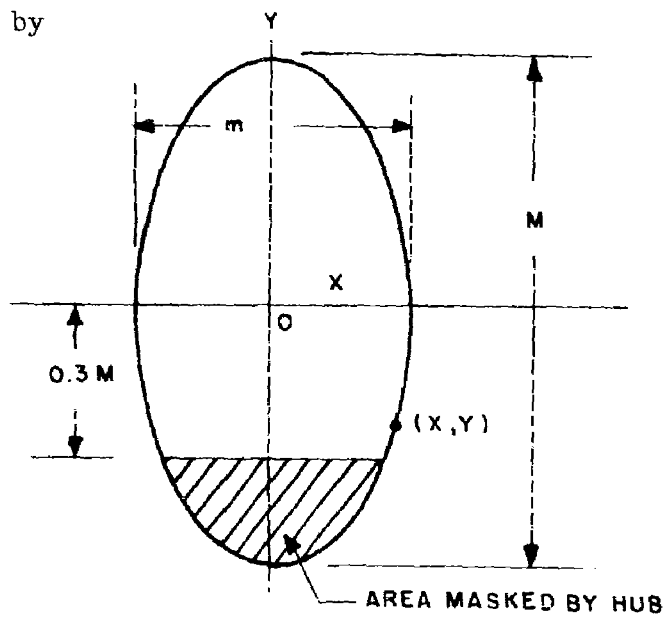

Figure 4 - Propeller Blade Outline

$$\frac{\ell}{D} = \frac{1.8675\,\frac{A_e}{A_o}}{Z(1-x_h)}\sqrt{1 - 4\left[\frac{0.8(x-x_h)}{(1-x_h)} - 0.3\right]^2} \qquad [2]$$

In addition to the nondimensional geometry, the actual propeller diameters used in the series are:

Hub Ratio	Tip Diameter in feet	
x_h	Bow Propellers	Stern Propellers
0.7	31.2	29.6
0.8	27.2	25.8

where, of course, each hub diameter is equal to the hull diameter at each propeller location.

THEORY AND CALCULATION OF WAKE-ADAPTED PROPELLERS

As stated earlier, Lerbs'[7] theory for moderately loaded propellers considers propellers having finite hub, finite number of blades, and a radial distribution of bound circulation Γ such that $\Gamma = 0$ at $x = x_h$. His theory is based on potential flow theory and replaces the propeller blade by a lifting line. The inflow velocities required for the design of a wake-adapted propeller are based on the real flow.

Calculations for moderately loaded propellers using Lerbs' induction-factor method are programmed[11] for a high-speed digital computer at the Model Basin. The problem is to find the optimum radial distribution of hydrodynamic pitch angle β_i (see Figure 5) to produce the design thrust of power. Design calculations for the propeller series developed in the present study are for a constant thrust of 80,000 pounds and constant ship speed of 30 knots. For wake-adapted propellers, the local speed-of-advance at each blade section is different, and because of this, the various coefficients are nondimensionalized on ship speed. For the cases considered, the resulting design thrust coefficients C_{T_S} based on propeller swept area are:

Hub Ratio	C_{T_s}	
x_h	Bow Propellers	Stern Propellers
0.7	0.0806	0.0898
0.8	0.1500	0.1675

In contrast to necessity of determining the corrections to section camber and pitch for a complete propeller design,[12] the theoretically estimated propeller performance in this study is predicted by simply introducing a viscous drag force as shown in Figure 5. The effect of this drag force on the nonviscous propeller thrust and power coefficients can be derived from the geometrical relationships of Figure 5.

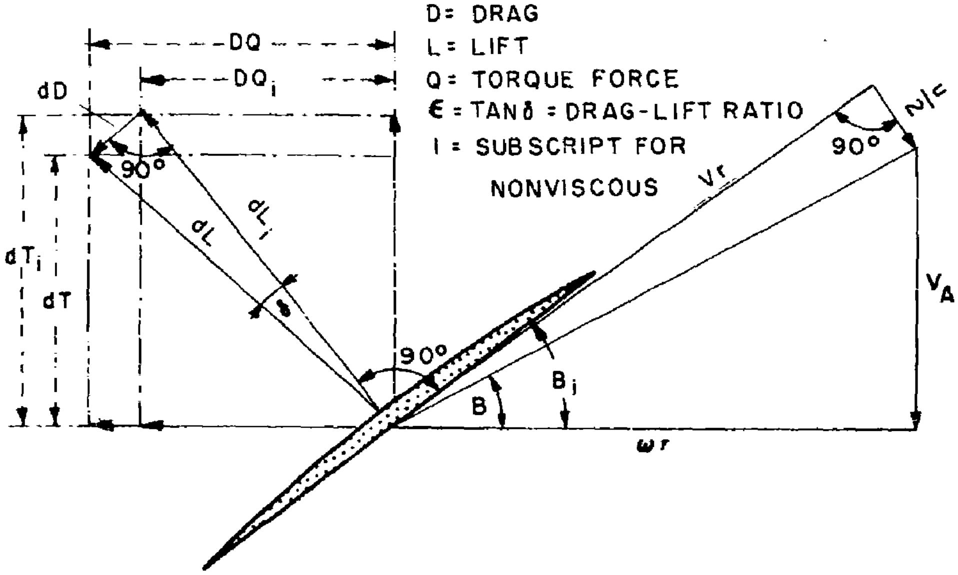

Figure 5 - Force Diagram of Viscous Flow at a Blade Section

In terms of drag-lift ratio ϵ and hydrodynamic pitch angle β_i, the viscous thrust and power coefficients C_{T_s} and C_{P_s} are[12]

$$C_{T_s} = \int_{x_h}^{1} (1 - \epsilon \tan \beta_i) \frac{dC_{Tsi}}{dx} dx \qquad [3]$$

$$C_{P_s} = \int_{x_h}^{1} (1 + \frac{\epsilon}{\tan \beta_i}) \frac{dC_{Psi}}{dx} dx \qquad [4]$$

In terms of Equations [3] and [4] and local velocity ratio V_x/V, propeller efficiency η_B in the wake-adapted condition is defined as

$$\eta_B = \frac{T\,V_a}{P_D} = \frac{\int_{x_h}^{1}\left(\frac{V_x}{V}\right)(1 - \epsilon \tan \beta_i)\,\frac{dC_{Tsi}}{dx}\,dx}{C_{P_s}} \qquad [5]$$

where P_D is power delivered to the propeller and the distribution of the nonviscous thrust and power coefficients is understood to be for the prescribed wake.

The optimum loading distribution has not been rigorously formulated for wake-adapted propellers, but Lerbs has derived an approximate formula for the optimum $\tan \beta_i$ distribution by assuming a uniform radial distribution of the thrust-deduction fraction. Lerbs' distribution[7,8] for $\tan \beta_i$ is

$$\tan \beta_i \approx \frac{\lambda_s\left(\frac{V_a}{V}\right)^{1/2}\left(\frac{V_x}{V}\right)^{1/2}}{x\,\eta_i} \qquad [6]$$

where $\tan \beta_i$ is the tangent of the hydrodynamic pitch angle,

$\lambda_s = \frac{V}{\pi n D}$ is the advance coefficient

V_a/V is the effective velocity ratio (see Assumption 2, Statement of Problem),

V_x/V is the local velocity ratio,

x is the radius fraction, and

η_i is the ideal propeller efficiency.

Kramer's curves,[12] which were calculated by assuming a range of values of β and β_i and integrating the differential equations for nonviscous thrust and power coefficients of free-running propellers, are used to obtain a first estimate of η_i. Equation [6] gives a distribution of $\tan \beta_i$ based on an effective velocity ratio, taken here as $V_{\bar{x}}/V$. An iterative procedure is used to determine the final distribution of $\tan \beta_i$ for an assumed $C_{T_{si}}$. For the first estimate, the ratio c of nonviscous to viscous thrust coefficient $C_{T_i}/C_T = c$ is estimated from the relations given in the propeller design method of Eckhardt and Morgan[12] and an approximate drag-lift ratio. These relations may be written

$$c = \frac{1}{1-2\,\varepsilon\,\lambda_i} \qquad [7]$$

$$\varepsilon \approx \frac{0.003065\,\frac{A_e}{A}}{C_T\,\lambda^2} \qquad [8]$$

and

$$\lambda_i = \frac{\lambda_s\,\frac{V_a}{V}}{\eta_i} \qquad [9]$$

A first estimate of C_{T_i} based on swept area is determined, from the above procedure, for entering Kramer's curves. It is essential to use swept area since the Kramer curves are for zero propeller hub.* Under some conditions encountered in the series, a combination of relatively small λ and large expanded-area ratio results in drag-lift ratios ε that are quite large; e.g., $\varepsilon > 0.5$. Equation [7] cannot be used in these cases, and it is necessary to obtain at least three solutions for nonviscous thrust using a suitable range of the constant c. Propeller thrust in a viscous flow is computed, and the ratio of nonviscous to viscous thrust is found for the design viscous thrust coefficient. Using the value of c thus found, a final calculation is performed.

Lerbs' theory is used to obtain the distribution of nonviscous thrust coefficient and power coefficient in Equations [3] and [4]. $C_{T_{si}}$ and $C_{P_{si}}$ are functions of the circulation, the advance angle β and the propeller-induced velocity. Using the estimated data discussed as input, a numerical solution is obtained from a high-speed computer program.[11]

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*Shultz[13] recalculated Kramer's curves for propellers having finite hubs for hub ratios up to 0.4. A comparison between the ideal efficiency η_i obtained for the maximum hub size and number of blades ($x_h = 0.4$ and $Z = 6$) reported by Shultz revealed excellent agreement with η_i as obtained by using swept area and Kramer's curves for zero hub.

PRESENTATION AND DISCUSSION OF RESULTS OF OPTIMUM PROPELLER SERIES

Figures 6 through 10 give optimum propeller efficiencies η_B for the series as computed from Equations [3], [4], and [5]. The efficiencies are plotted as a function of speed coefficient J in Figures 6 through 8 and cross-plotted as a function of expanded-area ratio A_e/A_o in Figures 9 and 10. As discussed in the previous section, these propeller efficiencies are for a constant thrust and ship speed. Each graph of η_B versus J is for a constant A_e/A_o for bow and stern propellers with 0.7 and 0.8 hub ratios. The cross plots of η_B versus A_e/A_o for bow and stern propellers with 0.7 and 0.8 hubs are presented at the J value which gave maximum η_B and also with J as a parameter. Although each set of curves in open-water series charts shows the complete performance of a single propeller for a range of J, in contrast each point on the present series of curves represents a different propeller.

Considering the salient features shown by the curves of Figures 6 through 8, it is seen that there is a J which gives maximum η_B for each curve. In general, higher efficiency for both bow and stern propellers is obtained with 0.7 hub ratios than with 0.8 hub ratios except in the range $J < 1.5$, where the efficiency curves for 0.7 and 0.8 hub ratios collapse into a single curve.

An examination of the cross plots of efficiency η_B versus A_e/A_o in Figure 9 reveals, as would be expected, the decline in η_B with increasing A_e/A_o for all conditions. In Figure 10 the comparison of maximum efficiences η_B for bow and stern propellers shows that optimum efficiencies of the same order of magnitude are obtained with either bow or stern propellers and that a 0.7 hub ratio results in efficiencies η_B about seven points higher than those for a 0.8 hub ratio at all A_e/A_o.

EXAMPLE FOR A TANDEM PROPELLER SUBMARINE

OPTIMUM PROPELLER EFFICIENCY DERIVED FROM SERIES

The selection of hull form and size for the hypothetical TPS has been discussed. An estimated 80 x 10^3 pounds of thrust per propeller were assumed from existing data for propelling a hull with bridge fairwater at 30 knots. Based on these postulated conditions, curves of optimum

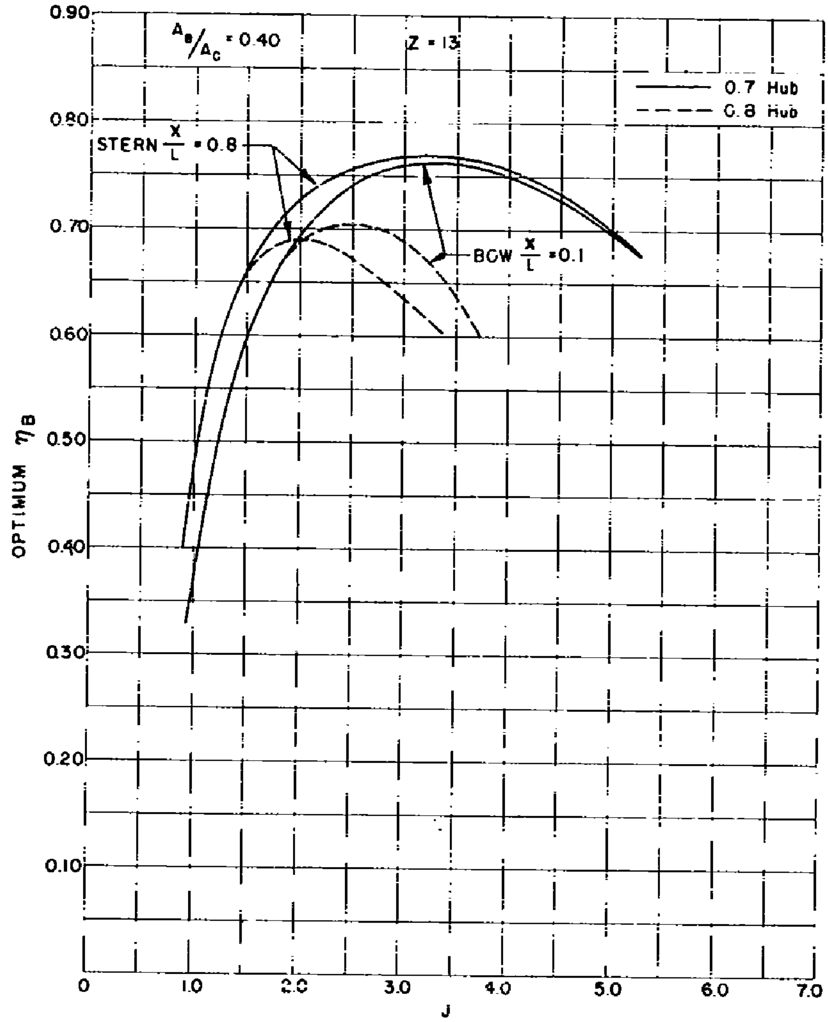

Figure 6 - Optimum Propeller Efficiency η_B versus Speed Coefficient for Series Propellers, $A_e/A_o = 0.4$

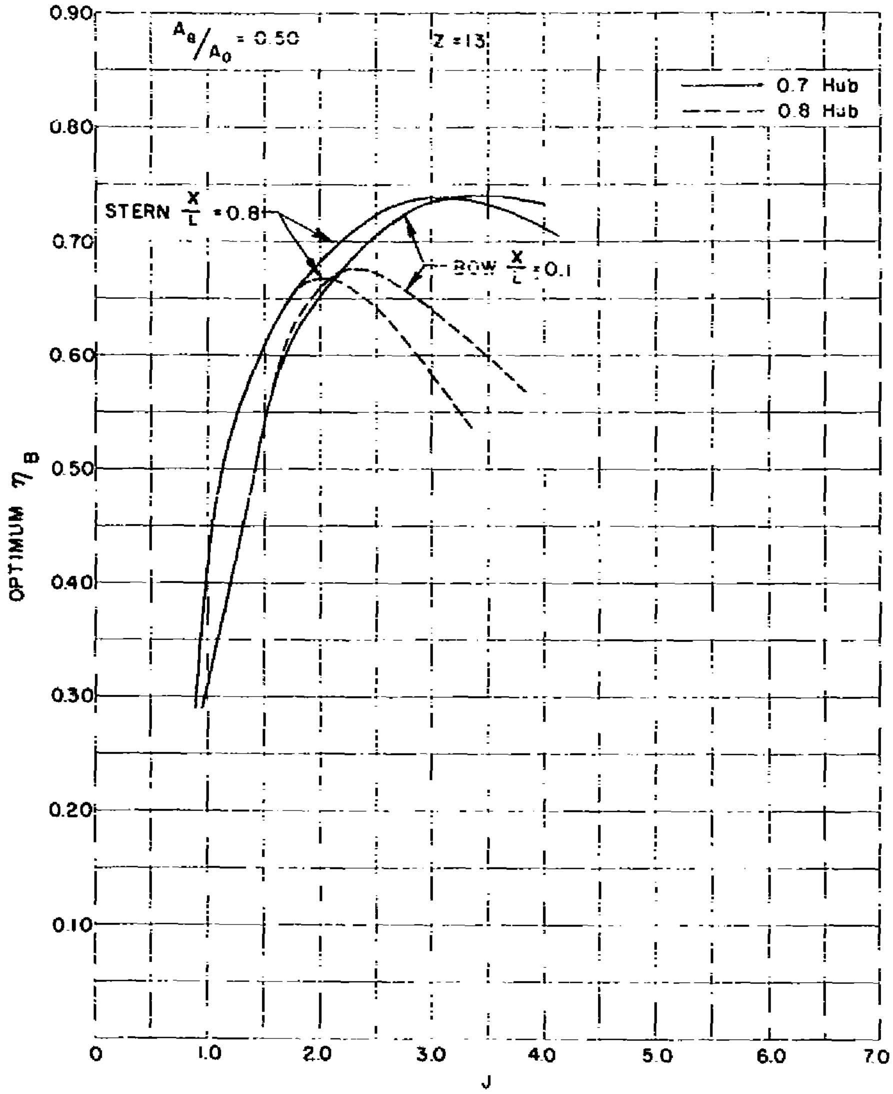

Figure 7 - Optimum Propeller Efficiency η_B versus Speed Coefficient for Series Propellers, $A_e/A_o = 0.5$

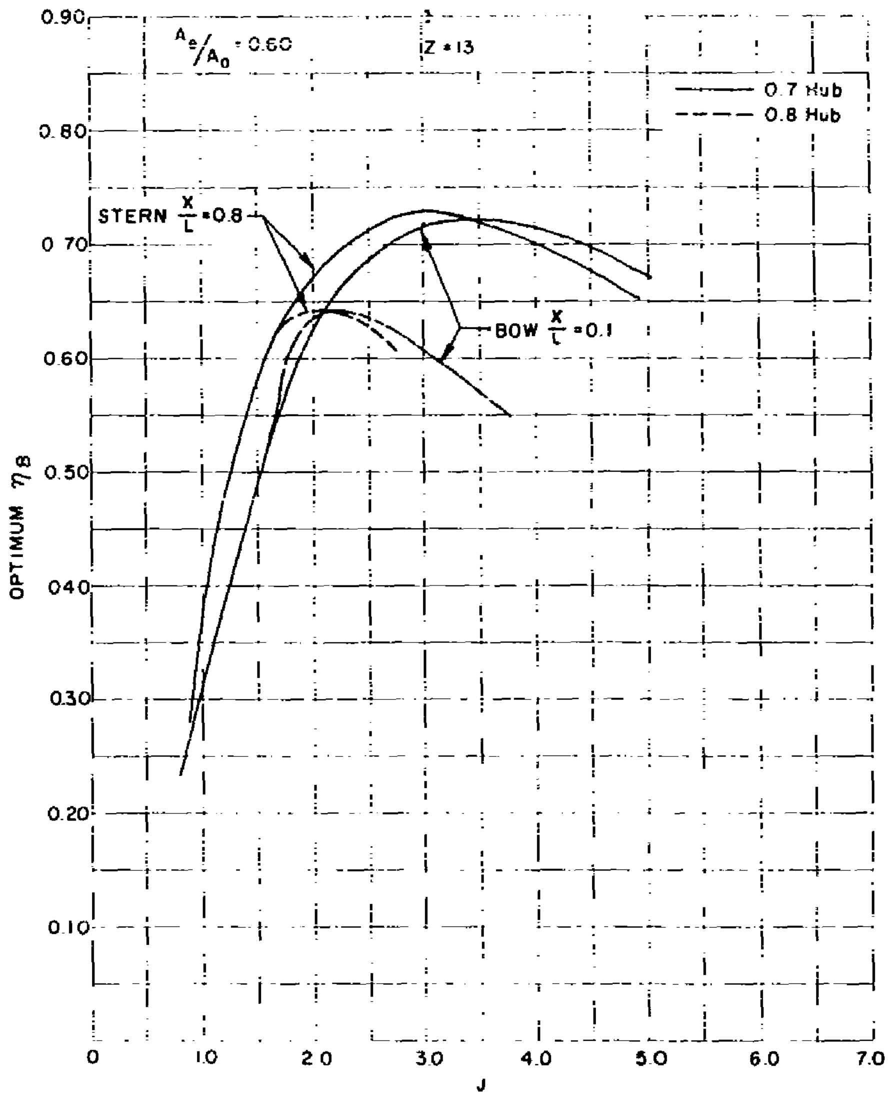

Figure 8 - Optimum Propeller Efficiency η_B versus Speed Coefficient for Series Propellers, $A_e/A_0 = 0.6$

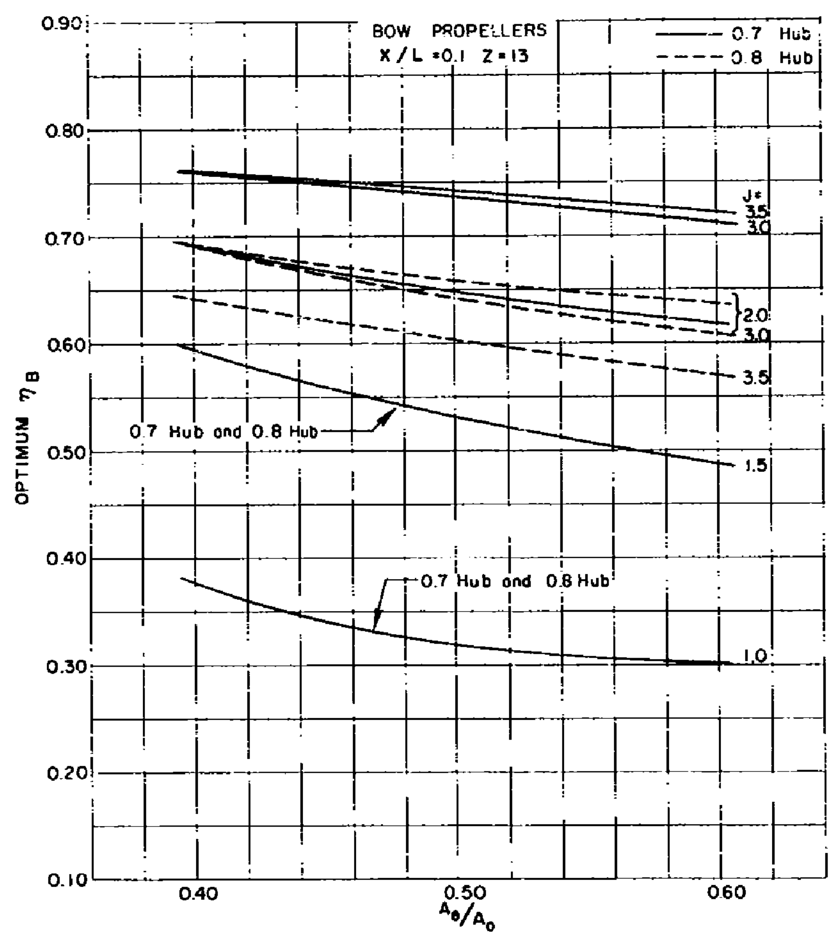

Figure 9a - Bow Propellers

Figure 9 - Optimum Propeller Efficiency η_B versus Expanded-Area Ratio for Series Propellers

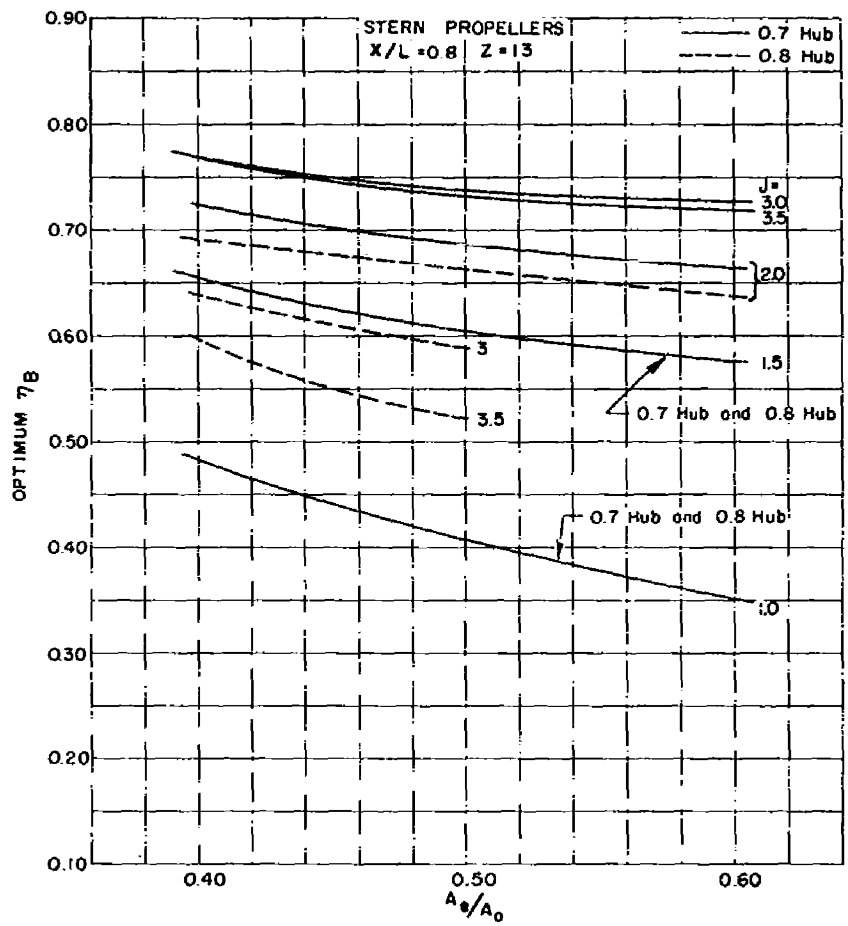

Figure 9b - Stern Propellers

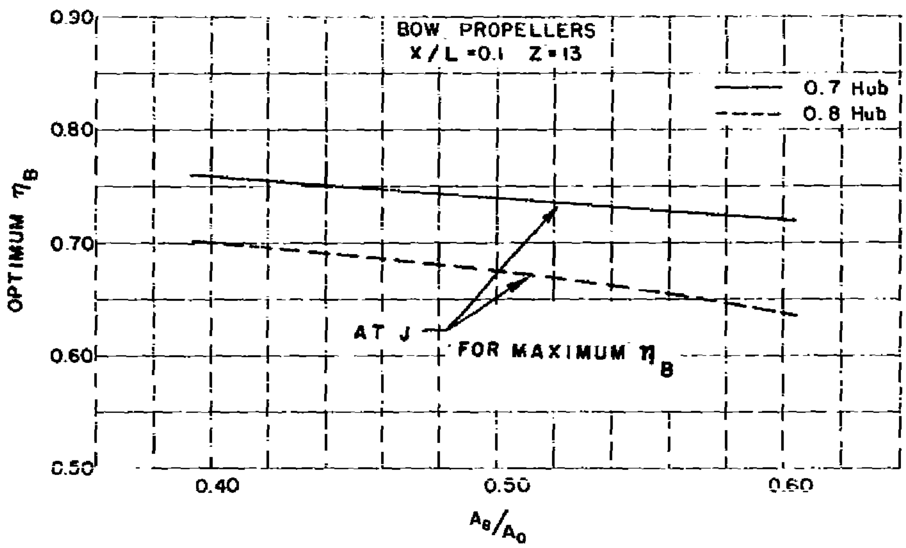

Figure 10a - Bow Propellers

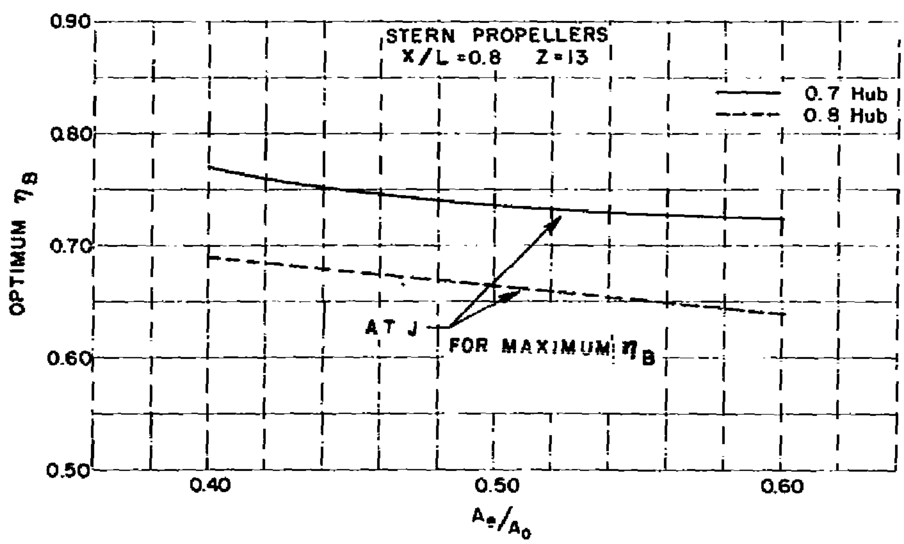

Figure 10b - Stern Propellers

Figure 10 - Optimum Propeller Efficiency η_B versus Expanded-Area Ratio for Series Propellers at J for Maximum η_B

efficiency η_B were derived from the series results in the last section and are plotted as a function of propeller rpm in Figures 11 through 13 for expanded-area ratios of 0.4, 0.5, and 0.6. Figure 14 shows the variation of efficiency η_B with expanded-area ratio for bow and stern propellers at a design rpm of 50. This design rpm of 50 was chosen based on information given in References 1, 3, and 4.

A summary of these results shows: (1) For bow propellers at a design rpm of 50, 0.8 hub ratio propellers have about a 3 point higher efficiency than 0.7 hub ratio propellers for all expanded-area ratios investigated. For stern propellers at 50 rpm, the difference in efficiency between 0.7 and 0.8 hub ratios is nil. (2) On the basis of operation at the best rpm, a 0.7 hub ratio is superior for both bow and stern propellers. Optimum efficiency η_B for this case is about 0.76 at an expanded-area ratio A_e/A_o of 0.4 as compared to $\eta_B \approx 0.70$ at 50 rpm for $A_e/A_o = 0.4$. (3) For all conditions, efficiency falls off above 50 rpm; however, in this range of higher revolutions the 0.8 hub ratio is best.

A word of caution is in order with regard to the superiority of 0.8 hub ratio bow propellers at 50 rpm. It can be seen in Figures 11 through 13 that maximum efficiency occurs in this region and that at lower rpm the efficiency drops rapidly. As mentioned previously, each point on these curves represents a design condition for an optimum wake-adapted propeller, and the sudden drop in η_B under the above conditions is not due to off-design performance. It should be realized, however, that optimum η_B is much lower and that off-design efficiency would be even lower.

COMPARISON WITH OTHER PROPULSION TYPES

To properly evaluate the powering performance of a TPS, it should be compared to conventional single-screw and counterrotating submarine propulsion. Ultimately, we wish to know the propulsion performance of the system, propellers plus hull, which may be analyzed by means of the propulsive coefficient η_D and its components.* A detailed discussion of η_D is

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*Propulsion performance comparisons of different submarine types on a basis of η_D are meaningful if their effective powers P_E are the same. In the present case, all comparisons are for the same resistance shape.

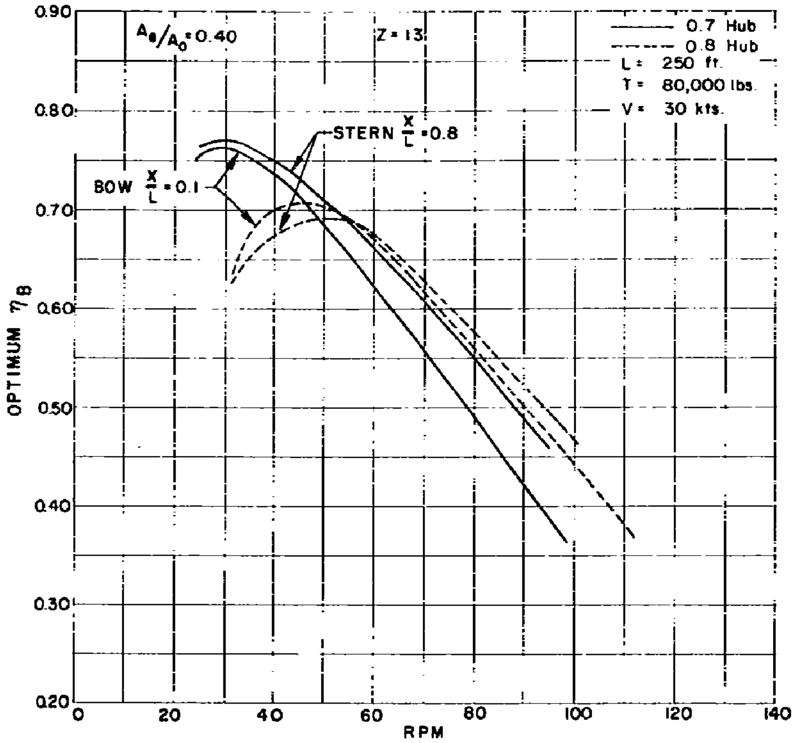


Figure 11 - Optimum Propeller Efficiency η_B versus RPM for a Hypothetical TPS, $A_e/A_o = 0.4$

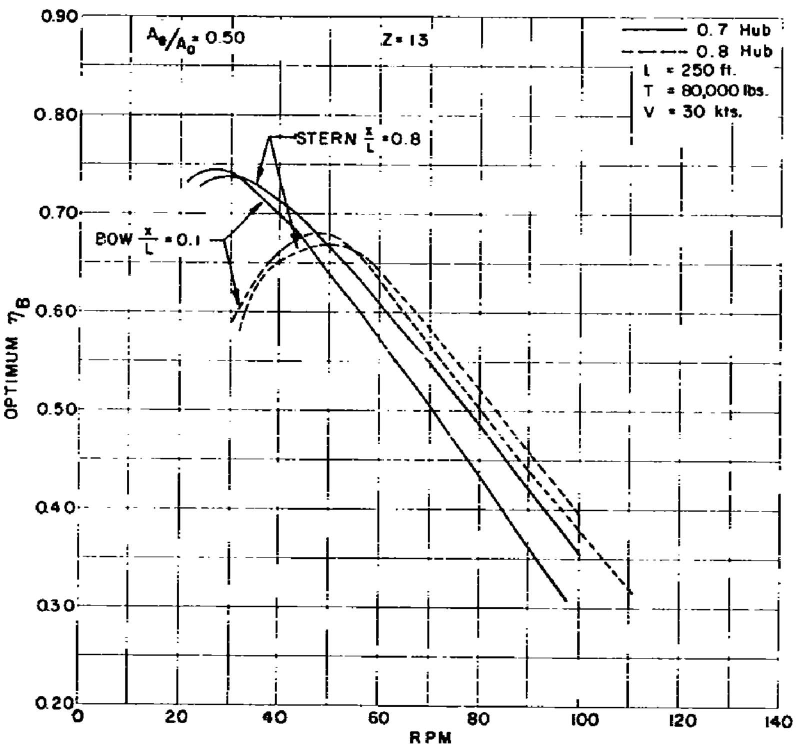


Figure 12 - Optimum Propeller Efficiency η_B versus RPM for a Hypothetical TPS, $A_e/A_o = 0.5$

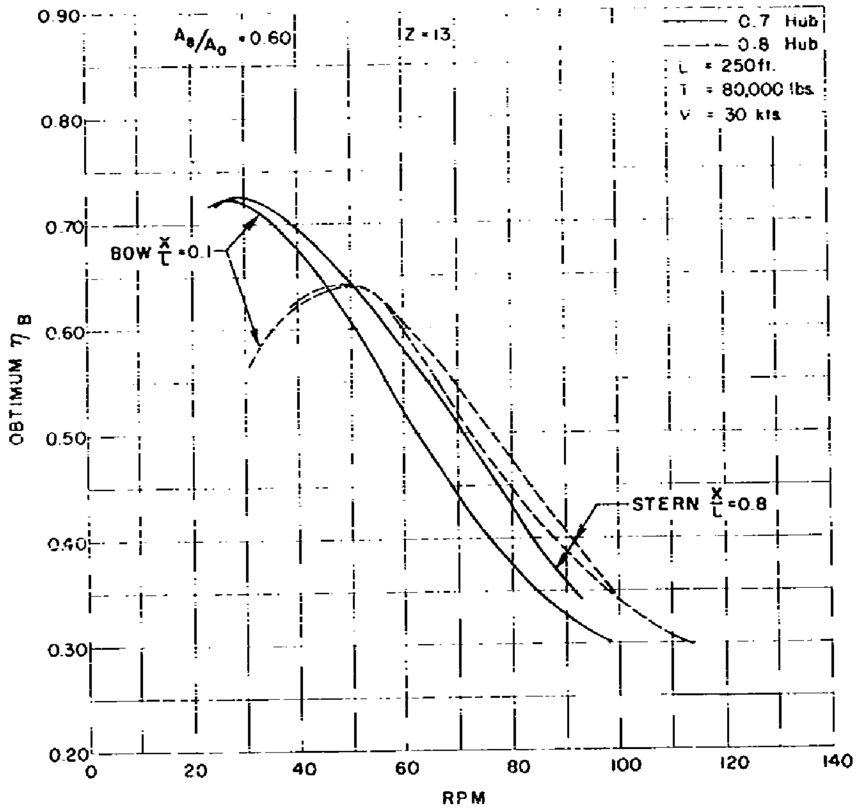
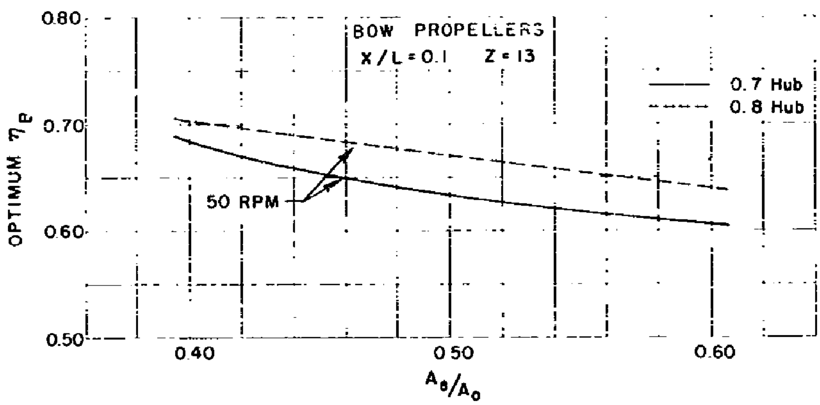


Figure 13 - Optimum Propeller Efficiency η_B versus RPM for a Hypothetical TPS, $A_e/A_o = 0.6$



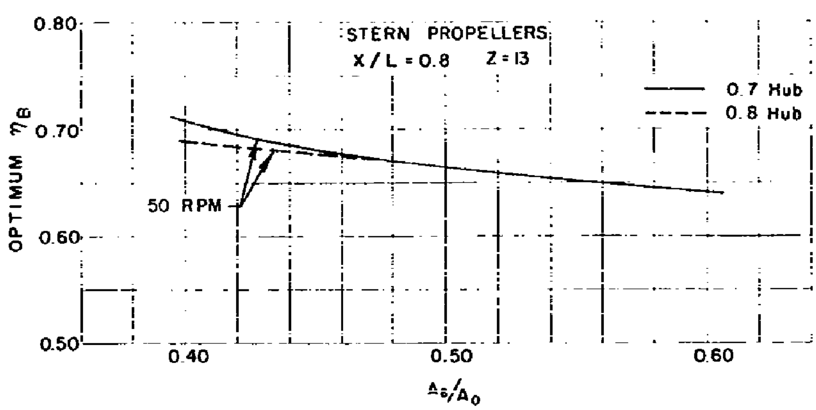


Figure 14 - Optimum Propeller Efficiency η_B versus Expanded-Area Ratio for a Hypothetical TPS

contained in Reference 14. The propulsive coefficient η_D is defined by

$$\eta_D = \frac{P_E}{P_D} = \frac{R_T\ V}{2\ \pi\ Qn} = \eta_H \cdot \eta_B \qquad [10]$$

where P_E is effective power,

P_D is power delivered to propeller,

R_T is hull resistance without propeller,

Q is propeller torque,

V is ship speed,

n is propeller rate of revolution,

η_H is hull efficiency, $= \frac{1-t}{V_a/V}$ and

η_B is propeller efficiency in a wake.

Having obtained η_B for a TPS, we now consider η_H and η_D. It seems reasonable to assume that $\eta_H < 1$ for a bow propeller of a TPS, since the effective velocity ratio V_a/V is essentially unity and a thrust deduction factor $(1-t) \leq 1$ could be expected. For a stern propeller at $X/L = 0.8$, the hull efficiency η_H would undoubtedly be less than that obtained with conventional stern propellers located farther aft where the average wake would be higher and the thrust deduction would probably be lower for usual streamline bodies of revolution. For the TPS, an optimum η_B of about 0.70 at 50 rpm and $A_e/A_o = 0.4$ would give a propulsive coefficient η_D of 0.7 η_H. A conventional submarine propulsion system would yield:

Single-screw: $\eta_D = 0.85$

$\eta_H = 1.32$

Considering the foregoing, an optimistic estimate of η_D for a TPS can be made as follows: For the <u>bow propeller</u>, let $\eta_D = 0.70 \times 1.0 = 0.70$. For the <u>stern propeller</u>, assume η_D equal to the 0.85 for single-screw propulsion. If an η_D of 0.85 could be achieved for the stern propeller of a TPS, then the average η_D for both propellers is 0.775. Thus, in regard to the propulsive coefficient it appears that the TPS does not compare favorably with normal propulsion types.

Feathering the forward motor for cruising has been suggested.[1] At a given cruising speed, this doubling the load effect on the stern propeller results in rather poor off-design performance, and the collective pitch must be reduced with a consequent lowering of efficiency. From this standpoint, depending on machinery characteristics, it would be more efficient to cruise with both bow and stern propellers thrusting. It must also be remembered that roll stabilization is accomplished by equal and opposite propeller torque.

CONCLUDING REMARKS

Using Lerbs' theory of moderately loaded propellers with appropriate viscous corrections, a series of design calculations was performed to determine the efficiency of optimum wake-adapted propellers having large hub ratios. Velocity profiles at bow and stern propeller locations of 0.10 body length and 0.8 body length were derived from boundary layer and potential flow theory for a body of revolution (minimum resistance form).

For constant thrust and 13 blades, the most important effects of speed coefficient, hub ratio, and expanded-area ratio on optimum propeller efficiency in a wake may be summarized as follows:

1. In general, for the same expanded-area ratios, higher optimum propeller efficiencies for both bow and stern propellers are obtained with 0.7 hub ratio than with 0.8 hub ratio except for $J < 1.5$, where the efficiency curves for 0.7 and 0.8 hub ratios collapse into a single curve.

2. As expected, propeller efficiency declines with increasing expanded-area ratio.

When the series results are applied to a hypothetical 250-foot tandem propeller submarine traveling at 30 knots, the following conclusions result:

1. At a design rpm of 50, bow propellers with 0.8 hub ratio have about a 3 point higher efficiency than propellers with 0.7 hub ratio.

2. For stern propellers at design rpm of 50, the difference in efficiency between 0.7 and 0.8 hub ratio is nil.

3. An optimum efficiency of about 0.70 is obtainable at 50 rpm and a 0.4 expanded-area ratio for the hypothetical TPS, and approximately 0.76 is obtainable at the best speed coefficient.

For a TPS design rpm of 50, an optimistic estimate of propulsive coefficient for TPS as compared to that for a conventional propulsion system shows:

Type	η_D
TPS	0.775
Single screw	0.85

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